FRACTURE TESTING OF HYBRID-FIBRE CONCRETE

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ABSTRACT
In order to determine the mechanical properties, pendulum-bar four-point bending, compressive and Young's Modulus test were performed. After the four-point bending test the specimens were impregnated with fluorescent epoxy resin in order to display the cracks in the inside of the specimen. The material that was used in this investigation contained fibre cocktails of two and three types of steel fibres. The middle displacement in the pendulum-bar four-point bending test is calculated from the displacement at the loading points.
An upper and lower limit was found for the middle displacement in this specific four-point bending test. The calculation for the upper limit is based on the intersection between the two lines given by the displacement under the loading points and the geometry of the test setup. The lower limit is based on dissipation energy on uncracked specimens.
The results from the pendulum-bar four point bending test show that the large fibres have an influence on the ductility and the maximum bending strength of HFC as well.
The crack pattern, derived from the cut specimens which were tested in the pendulum-bar four-point bending test, showed that macrocracks are not necessarily through-cracks, some of them are split into two cracks combined with some smaller cracks. It was also shown that there is not only one single crack but rather a crack-zone with only one crack going to the bottom of the specimen. When the crack becomes wide enough it will ultimately lead to a singe crack.

1 INTRODUCTION

The main aim of this work is to develop a material with large ductility and high tensile strength. Such a material can be used in walls where big deformations appear, for example during earthquakes. In order to sustain such a deformation, both ductility and the load resistance has to be high enough. Therefore, the Institute of Structural Engineering (IBK) at ETH was interested in building an earthquake-wall using the hybrid-fibre concrete developed at IfB. The mechanical demand of the material that was wanted was a HFC with 2% of fibres only, an ultra high ductility, some tensile strength and a large post-peak part with hardly any loss of load-bearing capacity. The compressive strength should be around 100 MPa. The limit of 2% fibres was given by the mixer that was used. The used mixer was never used before for HFC, and it had to be guaranteed that the mixer was up to its task. After a first series with 2% of fibres only, the amount of fibres was raised up to 3.5%, because the mixer was capable to mix it and the ductility of the initial material was not sufficient. After adjusting the mixture the mechanical properties, such as ductility, were acceptable. All the fibres used are the same as in [1,2]. In order to assess these mechanical properties, for both, the material with two and the one with three an a half percent of fibres, four-point bending tests were performed. For the second material compressive and Young's modulus tests were also performed. After testing, the cracked four-point bending test specimens were impregnated with epoxy resin and cut into slices to display the cross sections of the crack patterns inside the specimen. This method was already used in [2]. Some of these cross sections are shown in Paragraph 4.

2 MECHANICAL TESTS

To determine the mechanical properties standard compressive and Young's modulus tests and the pendulum-bar four-point bending tests were performed, see also [1]. The displacement controlled unaxial compression test was performed on cylinders with a diameter of 150mm and a height of 300mm and cubes of different geometry, namely 150mm and 70mm, while the pendulum-bar four-point bending test was performed on 70x70x280mm prisms.

2.1 Young's modulus and compression test

To determine the Young's modulus cylinders of the height of 300mm and the diameter of 150mm were used. After this standard test, the same cylinders were used for compression test as well. 150mm cubes were used to determine the uniaxial compression strength. After testing the 70x70x280 specimens in the four-point bending test, the same specimens were also used for compression tests on 70mm cubes. The 70mm cubes were obtained by cutting, the prisms 70mm from the side which was not influenced by the four-point bending test.

2.2 Pendulum-bar four-point bending test

The test and the measuring arrangements has been already reported in [1, 2]. A new approach to assess of the middle displacement in the pendulum-bar four-point bending test is introduced in this paper. In [1], the middle displacement has been calculated as the intersection of the two straight lines given by the displacement at the loading points and the geometry of the setup (see Fig. 1a and Eq. (1)). However, this calculation is a good approximation for the maximum value of the middle displacement, but only for the post-peak stage. There, a macro crack opens and "all" the deformations due to elasticity can be neglected because most of the deformation is caused by the macrocrack. In the pre-peak stage the deformation line is everything but a straight line (Fig. 1b) and all the deformations are influenced by non-linear elasticity. From elasticity theory, the deforming line can be calculated from the principle of virtual work (Eq. (2)). The calculation is given in Eqs. (3) to (7) and Figures 2 and 3 shows the principle sketches which the calculation was based on.

Eq. (1) gives the middle displacement based on the intersection of the two straight lines ,[1].

$$\delta_m = \frac{(2a+b)\cdot\delta_1\cdot\delta_2}{a\cdot(\delta_1+\delta_2)} \tag{1}$$

In Eq. (1), a is the distance between support and loading point and b the distance between the loading points. In Figure 1a δ_1 and δ_2 are the displacements at the loading points.

$$\delta = \int_0^{a+b+a} \overline{M_b}(x)\cdot\frac{M_b(x)}{E\cdot I}\cdot dx \tag{2}$$

$M_b(x)$ is the moment caused by the load and $\overline{M}b(x)$ is the moment caused by the virtual loading.

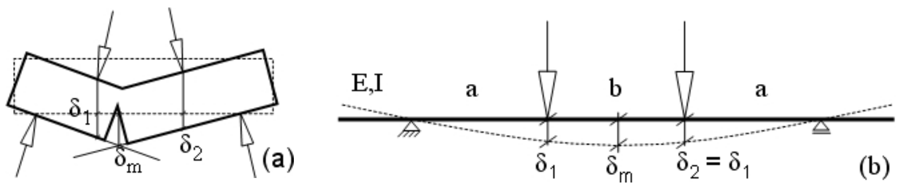

Figure 1: (a): Cracked deformation; (b): Elastic deformation

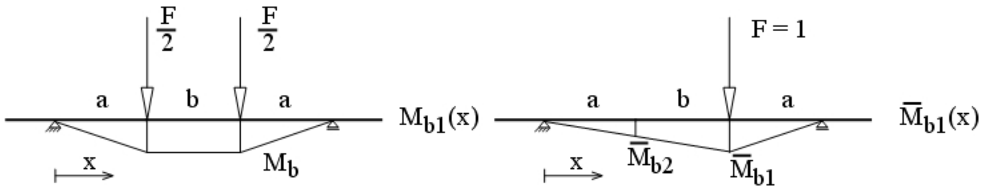

Figure 2: Sketch for calculating δ_1

$$\delta_1 = \frac{1}{E \cdot I}\left(\frac{1}{3} M_b \cdot \overline{M_{b2}} \cdot a + \frac{1}{2} M_b \cdot \left(\overline{M_{b1}} + \overline{M_{b2}}\right) \cdot b + \frac{1}{3} M_b \cdot \overline{M_{b1}} \cdot a\right) \tag{3}$$

$$\delta_1 = \frac{a^2 (2a+3b) \cdot F}{12 \cdot E \cdot I} \tag{4}$$

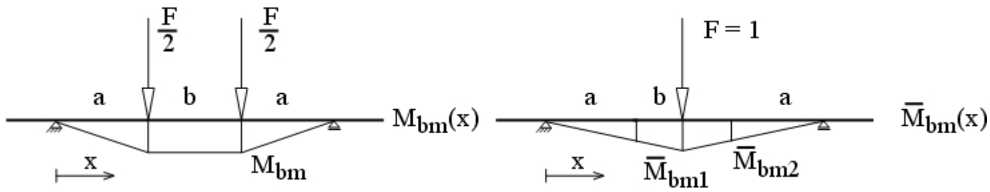

Figure 3: Sketch for calculating of δ_m

$$\delta_m = \frac{1}{E \cdot I}\left(\left(\frac{1}{3} M_b \cdot \overline{M_{bm2}} \cdot a + M_b \cdot \overline{M_{bm2}} \cdot \frac{b}{2} + \frac{1}{2} M_b \cdot \left(\overline{M_{bm1}} - \overline{M_{bm2}}\right) \cdot \frac{b}{2}\right) \cdot 2\right) \tag{5}$$

$$\delta_m = \frac{a \cdot (8a^2 + 12ab + 3b^2) \cdot F}{48 E \cdot I} \tag{6}$$

Combining Eq. (4) and Eq. (6), the middle deflection can be calculated as

$$\delta_m = \frac{\left(8a^2 + 12ab + 3b^2\right) \cdot \delta_1}{4a\left(2a + 3b\right)} \tag{7}$$

In Eq. (7) δ_1 is the average of the displacements at the loading points. Figure 4 shows the differences between the different methods of calculating δ_m.

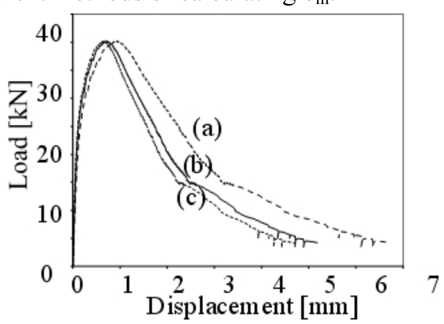

Figure 4: Differences between (a) calculation based on Eq. (7), (b) calculation based on Eq. (6), (c) average of the measured displacements at the loading points

3 MATERIAL

The used material was designed for an earthquake-wall which was tested at the Institute of Structural Engineering (IBK), at ETH Zurch the group of Prof. Dr. A. Dazio (Structural Dynamics and Earthquake Engineering). Several requirements have been imposed on the properties of the wall. First by the maximal amount of fibres was set to two percent. This limit has been set because it was assumed that the available mixer did not have enough power for larger volumes of fibres.

Another important point was the fibre-distribution. It had to be guaranteed that the fibres were well distributed. Usually, mixers with a planetary mixing gear were used but the mixer used was an ordinary rather old single-shaft mixer. Therefore a comparison between fibre-distribution due to the different mixers will have to be performed.

After a first series with 2% of fibres only (mixture 1.5/0/0.5) which indicates the percentage of short/middle/long fibres, see also Table 1, it was realized that the mixer had enough power to mix even more fibres. Moreover it is apparent that the material was not ductile enough. A new mixture was designed with larger volumes of the long fibres (0.6x30mm) and some of the middle sized fibres (0.2x12mm) (mixture 1.5/0.5/1.5). All the mix proportions are given in Table 1.

Table 1: Mixtures

	Mixture 1.5/0/0.5	Mixture 1.5/0.5/1.5
CEM I 52.5R	1000kg/m^3	1000kg/m^3
Fly-ash and Micro-silica	250kg/m^3	250kg/m^3
Sand 0-1mm	750kg/m^3	750kg/m^3
W/B-ratio	0.17	0.17
Superplasticizer (Glenium ACE 30)	2% of cement	2% of cement
Stee-lfibre 0.15x6mm	1.5%	1.5%
Stee-lfibre 0.2x12mm	0%	0.5%
Stee-lfibre 0.6x60mm	0.5%	1.5%

4 RESULTS

4.1 Four-point bending test results

All the results shown are averages out of 3 tests for mixture 1.5/0.5/1.5 and 6 test for the mixture

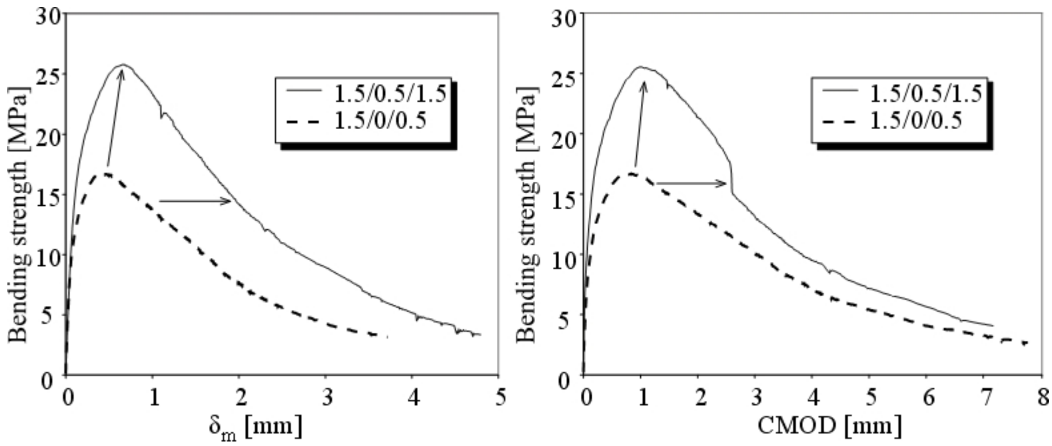

Figure 5: (a) Displacement δ_m vs. bending strength and (b) CMOD vs. bending strength

1.5/0/0.5 respectively. The middle-displacement was calculated based on Eq.. (6). In Figure 5 it can be seen, that the maximum bending strength and the ductility increases by adding long fibres.

It can also be seen that the stiffness decreases with the increase of the stress. This decrease starts at the very beginning of the curve.

4.2 *Standard test-results*

Table 2 shows the results from the compression and E-modulus test. All the tests were performed using a displacement-controlled loading machine.

Table 2: Results from the compressive and Young's modulus test. In brackets: coeff. of variation [-]

	Young's modulus [GPa]	Compressive strength (150mm cubes) [MPa]	Compressive strength (70mm cubes) [MPa]	Compressive strength (cylinder 30/Ø15) [MPa]
1.5/0/0.5	-	-	151.4 (0.03)	-
1.5/0.5/1.5	40.7 (0.01)	134.8 (0.04)	136.0 (0.04)	142.7 (0.03)

4.3 *Crack pattern of the 1.5/0.5/1.5 series*

After the pendulum-bar four-point bending test the tested specimens were impregnated and cut into four slices of 1.5cm thickness through the zone were the crack appeared. Each cut gave two pictures of the crack. The distance between such a pair of pictures was the width of the cutting blade, namely 4mm. A selection of some of the cracks is shown in Figure 6. Different phenomena can be observed and are discussed in Paragraph 5.

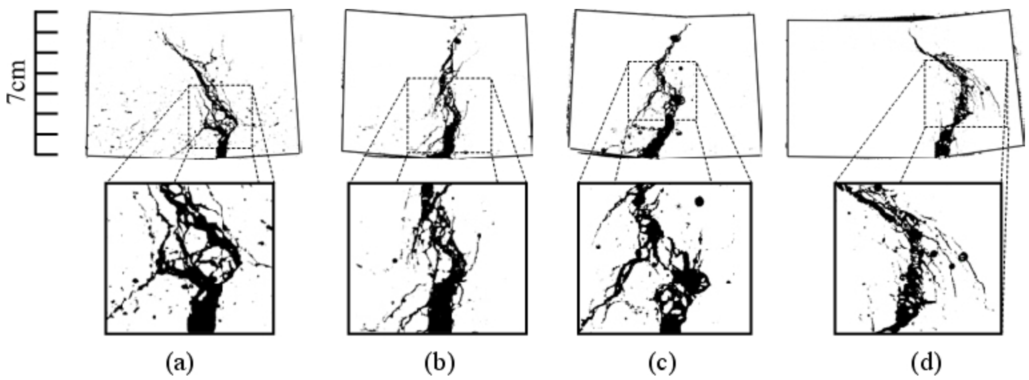

Figure 6: Crack pattern of different samples from mixture 1.5/0.5/1.5

5 DISCUSSION

5.1 *Calculation methods*

For several parameters such as fracture energy, it is important to have the middle displacement δ_m. In the pendulum-bar four-point bending test there are two methods for calculating δ_m as seen in paragraph 2.1. The results of both methods are not valid for the whole stress-displacement diagram. The middle displacement based on Eq. (7) is only valid for elastic displacement and the calculation based on the intersection of the two lines (Eq. (1) only for the case, where all the deformations are associated with a propagation of one single crack.

These two methods give an upper (Eq. (1)) and a lower (Eq. (7)) limits for the real middle displacement.

5.2 Four-point. bending results

The results derived from the four-point bending test clearly show that the stiffness decreases with the increase of the load. Microcracks develop from the very beginning of the test, this leads to the mentioned decrease of the stiffness. At the peak, a single macrocrack opens and all the deformations concentrate in that crack. Figure 5 shows that with the increase of the amount of long fibres the ductility and the bending strength increase. The increase of the bending strength could be explained from an increase of the fibre volume.

The reconstructed crack patterns show that the cracks do not develop through the specimen in one single line. It can be seen (Fig. 6c) that quite some bridging appeared in the macrocrack. Branching appears as the consequence of fibre bridging. Figure 6d also shows that the maximum width where the cracks appear is as wide as the maximum fibre length.

6 CONCLUSION AND OUTLOOK

The middle displacement in the pendulum-bar four-point bending test can be estimated from the displacement at the loading points. A minimum is given in Eq. (7) and a maximum in Eq. (1).

For material such as HFC, the role of the mixing technique becomes more and more important. At the Institute for Building Materials (IfB) two different mixing systems (planetary mixers and ordinary single-shaft mixer) are used. Investigations about strength, fibre-distribution or mixing time due to the mixing system must be carried out. However, in the future it is planed to have one mixing system only.

The bending strength and the ductility increases with the increase of the amount of large fibres, such as 30mm fibres.

Macrocracks do not necessarily have to be through-cracks. As can be seen in Figure 6 the cracks are not simple lines, there is more a zone of macrocracking and bridging appears to be quite important. This zone is in the lower third of the specimen. At the bottom of the specimen, only one macrocrack appears.

7 REFERENCES

[1] Stähli, P, van Mier, J.G.M (2004): Three-fibre-type hybrid fibre concrete - in proceeding FRAMCOS-5, Vail, USA, ed. V. C. Li et al, pp. 1105-1112

[2] Stähli, P, van Mier, J.G.M (2004): Rheological properties and fracture processes of HFC- to be published in Befib 2004, Como, Italy